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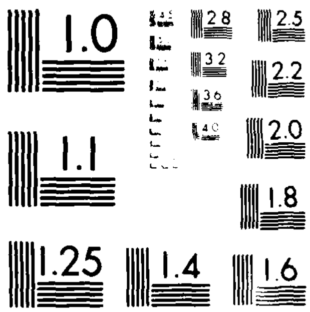

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFOSR-TR- 84-0527
2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): Nonlinear Dynamics of Multi-Channel Binocular Vision
5. TYPE OF REPORT & PERIOD COVERED: annual scientific report 2/1/83 - 1/31/84
6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): PROFESSOR STEPHEN GROSSBERG
8. CONTRACT OR GRANT NUMBER(s): F49620-83-C-0066
9. PERFORMING ORGANIZATION NAME AND ADDRESS: CENTER FOR ADAPTIVE SYSTEMS, MATHEMATICS DEPARTMENT, BOSTON UNIVERSITY, BOSTON, MA 02215
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 61102F, 2313/A5
11. CONTROLLING OFFICE NAME AND ADDRESS: AFOSR/LIFE SCIENCES DIRECTORATE, BOLLING AIR FORCE BASE, WASHINGTON, DC 20332
12. REPORT DATE: March 7, 1984
13. NUMBER OF PAGES: 18
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
15. SECURITY CLASS. (of this report): unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Vision, Movement, Rhythm

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Progress was made in three related areas: vision, movement, and rhythm. A real-time processing theory was introduced of how the visual system discounts several types of noise in visual data, yet rapidly generates global visual representations. These mechanisms can be interpreted both behaviorally and neurally. The mechanisms describe new parallel processing algorithms that operate within hierarchical net-

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works. Simulations were made of real and illusory contour formation, neon color spreading, complementary color induction, and filling-in. The theory physically interprets and generalizes Land's retinex theory of color vision, and unifies the explanation of monocular and binocular brightness data. The simulated data include Craik-O'Brien effects and their exceptions; the Bergström demonstrations comparing brightnesses of smoothly modulated and step-like luminance profiles; nonclassical differences between the perception of luminance decrements and increments; Fechner's paradox, binocular brightness averaging, and binocular brightness summation; binocular rivalry; and fading of stabilized images and ganzfelds. Two parallel contour processes interact to generate the theory's brightness, color, and form explanations.

A new theory of adaptive sensory-motor control was introduced and used to explain how ballistic eye movements are rapidly performed and adaptively self-calibrated in real-time. The theory's circuit designs can be applied to many problems in adaptive control theory and robotics. This theory describes how retinotopic maps, target position maps, motor maps, and temporal order maps are built up, transformed, and calibrated through learning. Circuits controlling intentional movements and automatic movement planning are described. These circuits explain data about superior colliculus, cerebellum, peripontine reticular formation, parietal cortex, and frontal eye fields.

A neural theory was developed of the circadian pacemaker in the hypothalamic suprachiasmatic nuclei. Effects of lighting regime on circadian period, phase, and activity levels were simulated. Applications to regulation of reinforcement, motivation, and attention were made. Similar mechanisms occur in perceptual networks. Applications to binocular rivalry and cognitive entrainment are being studied.

AFOSR-TR- 84-0327

Annual Scientific Report
F49620-83-C-0066
7 March 1984

NONLINEAR DYNAMICS OF MULTI-CHANNEL

BINOCULAR VISION

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SUMMARY OF RESULTS

A. VISION

Rapid progress has been made on several mutually supportive projects. In the area of visual perception per se, a new visual processing theory has been introduced that is capable of explaining a wide variety of data about depth, brightness, color, and form perception. No other single theory can explain the full range of these data. Moreover, many of the data have received no dynamical explanation before this time. The theory's processes can be neurally interpreted in terms of striate and prestriate cortical mechanisms, and make several testable predictions about cortical interactions. These visual processes are defined in a rigorous mathematical form that could be developed into practical real-time image processing software or hardware given sufficient funding.

The scope of the visual phenomena that have already been treated is illustrated by the enclosed Abstracts from completed research articles.

OUTLINE OF A THEORY OF BRIGHTNESS, COLOR, AND FORM PERCEPTION

Stephen Grossberg

This chapter describes new concepts and mechanisms from a real-time visual processing theory that has been used to explain paradoxical data about brightness and form perception. These data include the Craik-O'Brien effect, the Land brightness and color demonstrations, the fading of stabilized images, neon color spreading, complementary color induction, completion of illusory contours, and binocular rivalry. Two functionally distinct contour processes interact to generate these brightness and form properties in the theory. A Boundary Contour process in sensitive to the amount of contrast but not to the direction of contrast in scenic edges. It includes a binocular matching stage that is sensitive to spatial scale, orientation, and binocular disparity, and whose outcome triggers a process of monocular contour completion. These completed contours form the boundaries of monocular perceptual domains. A Feature Contour process is sensitive to both the amount of contrast and to the direction of contrast in scenic edges. It triggers a diffusive filling-in reaction of featural quality within perceptual domains whose boundaries are dynamically defined by the completed boundary contours. The diffusive filling-in reactions take place within syncytia of cell compartments. These preprocessed monocular representations give rise to a percept via a process of binocular resonance. The percept takes the form of standing waves of patterned activity among multiple spatial scales. The Boundary Contour process is hypothesized to be analogous to interactions between the hypercolumns in area 17 of the visual cortex. The Feature Contour process is hypothesized to be analogous to interactions between the cytochrome oxydase staining blobs in area 17 and prestriate cortex in area 18.

THE QUANTIZED GEOMETRY OF VISUAL SPACE:

THE COHERENT COMPUTATION OF DEPTH, FORM, AND LIGHTNESS

Stephen Grossberg

A theory is presented of how global visual interactions between depth, length, lightness, and form percepts can occur. The theory suggests how quantized activity patterns which reflect these visual properties can coherently fill-in, or complete, visually ambiguous regions starting with visually informative data features. Phenomena such as the Cornsweet and Craik-O'Brien effects, phantoms and subjective contours, binocular brightness summation, the equidistance tendency, Emmert's law, allelotropia, multiple spatial frequency scaling and edge detection, figure-ground completion, coexistence of depth and binocular rivalry, reflectance rivalry, Fechner's paradox, decrease of threshold contrast with increased number of cycles in a grating pattern, hysteresis, adaptation level tuning, Weber law modulation, shift of sensitivity with background luminance, and the finite capacity of visual short term memory are discussed in terms of a small set of concepts and mechanisms. Limitations of alternative visual theories which depend upon Fourier analysis, Laplacians, zero-crossings, and cooperative depth planes are described. Relationships between monocular and binocular processing of the same visual patterns are noted, and a shift in emphasis from edge and disparity computations towards the characterization of resonant activity-scaling correlations across multiple spatial scales is recommended. This recommendation follows from the theory's distinction between the concept of a structural spatial scale, which is determined by local receptive field properties, and a functional spatial scale, which is defined by the interaction between global properties of a visual scene and the network as a whole. Functional spatial scales, but not structural spatial scales, embody the quantization of network activity that reflects a scene's global visual representation. A functional scale is generated by a filling-in resonant exchange, or FIRE, which can be ignited by an exchange of feedback signals among the binocular cells where monocular patterns are binocularly matched.

NEURAL DYNAMICS OF FORM PERCEPTION:
CONTOUR COMPLETION, ILLUSORY FIGURES, AND NEON COLOR SPREADING

Stephen Grossberg and Ennio Mingolla

A real-time visual processing theory is used to analyse real and illusory contour formation, interactions between contour and brightness effects, neon color spreading, complementary color induction, and filling-in of discounted illuminants and scotomas. The theory also physically interprets and generalizes Land's retinex theory. These phenomena are suggested to arise from adaptive processes which overcome limitations of visual scanning to synthesize informative visual representations of the external world. Two functionally distinct contour processes interact to generate the theory's brightness, color, and form estimates. A Boundary Contour process is sensitive to the orientation and amount of contrast but not to the direction of contrast in scenic edges. It includes a binocular matching stage that is sensitive to spatial scale, orientation, and binocular disparity, and whose outcome triggers a process of monocular contour completion. These completed contours form the boundaries of monocular perceptual domains. A Feature Contour process is sensitive to both the amount of contrast and to the direction of contrast in scenic edges. It triggers a diffusive filling-in reaction of featural quality within perceptual domains whose boundaries are dynamically defined by the completed boundary contours. The Boundary Contour process is hypothesized to be analogous to interactions initiated by the hypercolumns in area 17 of the visual cortex. The Feature Contour process is hypothesized to be analogous to interactions initiated by the cytochrome oxydase staining blobs in area 17.

NEURAL DYNAMICS OF BRIGHTNESS PERCEPTION: FEATURES, BOUNDARIES, DIFFUSION, AND RESONANCE

Michael A. Cohen and Stephen Grossberg

A real-time visual processing theory is used to unify the explanation of monocular and binocular brightness data. This theory describes adaptive processes which overcome limitations of visual scanning to synthesize informative visual representation of the external world. The brightness data include versions of the Craik-O'Brien-Cornsweet effect and its exceptions, demonstrations comparing the brightnesses of smoothly modulated and step-like luminance profiles, nonclassical differences between the perception of luminance decrements and increments, Fechner's paradox, binocular brightness averaging, binocular brightness summation, binocular rivalry, and fading of stabilized images and ganzfelds. Familiar concepts such as spatial frequency analysis, Mach bands, and edge contrast are relevant but insufficient to explain the totality of these data. Two parallel contour processes interact to generate the theory's brightness, color, and form explanations. A Boundary Contour process is sensitive to the orientation and amount of contrast but not to the direction of contrast in scenic edges. It generates contours that form the boundaries of monocular perceptual domains. A Feature Contour process is sensitive to both the amount of contrast and to the direction of contrast in scenic edges. It triggers a diffusive filling-in reaction of featural quality within perceptual domains whose boundaries are dynamically defined by boundary contours. The Boundary Contour system is hypothesized to include the hypercolumns in visual striate cortex. The Feature Contour system is hypothesized to include the blobs in visual striate cortex. Monocular brightness domains enter consciousness in the theory via a process of resonant binocular matching that is capable of selectively lifting whole monocular patterns into binocular perception. This process is hypothesized to occur in visual prestriate cortex.

B. SENSORY-MOTOR CONTROL

Visual representations influence and are influenced by processes of motor control. A real-time theory has been developed concerning the adaptive control of ballistic eye movements. Such movements are generated in response to multiple visual cues and as part of intentional motor programs. They are extremely rapid and remarkably precise. The eye movement system can also adaptively recalibrate its parameters during normal development or after accidental lesions, despite the fact that no component of the system knows what any other component is doing.

A series of novel design principles and explicit real-time control circuits have arisen from this study. These principles promise to generalize to the design of other sensory-motor systems. We will, for example, soon analyse how eye and arm motions learn each other's operating parameters, and how arm movements can be rapidly generated by visual commands.

Our circuits for the control of eye movements were derived from concepts about how eye movement errors are corrected during normal development or after certain adult lesions. These circuits have already been used to analyse data concerning the role of retina, superior colliculus, peripontine reticular formation, cerebellum, parietal cortex, frontal eye fields, and oculomotor nuclei in eye movement control. This analysis suggests how the system learns to transform visually initiated intended target position commands into motor commands using outflow motor signals; how to compute motor commands that transform intended target position commands into retinotopic commands that automatically compensate for present position; how to calibrate outflow signals to nonlinear motor plants, including damaged plants, using comparisons with inflow signals; how to rapidly alter movement commands in response to changing plans; how to organize and rapidly read-out predictive sequences of pre-planned motions; how to separately calibrate the gains that maintain motor posture and that control active movements; how to guarantee recovery from lesions of one command source by adaptive redistribution of processing load to cooperating command sources. A new computational language is developed with which to describe the new concepts and mechanisms of the theory.

The enclosed Abstract lists some of the types of data that can be explained using this theory. This theory's circuits can also be used to generate real-time software or hardware for visually mediated or preprogrammed movement planning, given sufficient funding.

ADAPTIVE NEURAL DYNAMICS OF THE SACCADIC EYE MOVEMENT SYSTEM

AND GENERAL PRINCIPLES OF SENSORY-MOTOR CONTROL

Stephen Grossberg and Michael Kuperstein

Neural circuits for the control of saccadic eye movements are derived from concepts about how saccadic errors are corrected during normal development or after certain adult lesions. These circuits are used to analyse data concerning the role of retina, superior colliculus, peripontine reticular formation, cerebellum, parietal cortex, frontal eye fields, and oculomotor nuclei in eye movement control. The design principles that these circuits instantiate are common to many other sensory-motor systems. We analyse how to calibrate head coordinate maps that transform intended target position commands into agonist-antagonist muscle coordinates using corollary discharge signals; how to compute neural vectors that transform intended target position commands into retinotopic commands that automatically compensate for present position; how to calibrate outflow signals to nonlinear muscles using comparisons with inflow signals; how to attentionally and intentionally modulate movement commands; how to organize and rapidly read-out predictive sequences of pre-planned motions; how to separately calibrate the gains that maintain posture and that control movements; how to explain recovery from lesions of one neural region by adaptive redistribution of processing load to functionally related regions. A functional language is developed with which to describe the new concepts and mechanisms of the theory. Many of these concepts and mechanisms can be used to analyse other sensory-motor systems and to suggest new designs of self-calibrating robots. Applications include explanations of double-flash experiments (Hallett and Lightstone, 1976), flash-electrode experiments (Mays and Sparks, 1980; Guthrie, Porter, and Sparks, 1983), experiments on independent frontal eye field and superior colliculus saccadic control (Schiller and Sandell, 1983), experiments on visually-guided arm pointing after strabismus surgery (Steinbach and Smith, 1981), experiments on corrective saccades in the dark (Shebilske, 1977), experiments on independent cerebellar control of pulse and step gains (Optican and Robinson, 1980), experiments on fractured somatotopy (Bower and Woolston, 1983), experiments on inhibition of parietal

light-sensitive neurons during saccades (Yin and Mountcastle, 1977), experiments on saccade staircases (Hikosaka and Wurtz, 1983; Schiller and Stryker, 1972), experiments on adaptation to curvature-distorting contact lens (Epstein, 1977; Slotnick, 1969; Welch, 1978). Many predictions follow from the explicit nature of the model circuits.

C. RHYTHM

A large number of biological processes are under circadian control, or are otherwise entrained by rhythmic constraints. Our neural theory of circadian rhythms has been used to quantitatively simulate a wide variety of parametric circadian data concerning the short-term and long-term effects of lighting regime on circadian period, phase, and activity cycles. The mechanisms used in this theory have also been used, in different parameter ranges and circuit wiring diagrams, to simulate parametric data concerning the transduction of light into electrical potential by vertebrate photoreceptors, and to suggest explanations of a large interdisciplinary data base concerning how reinforcement, drive, motivation, and attention mechanisms interact to control the allocation of behavioral resources through time.

A design module called a gated dipole circuit has hereby been shown to be of major importance in all of these data domains. This module has also been used to explain data about memory search, cognitive self-organization, and perceptual switching. The circadian results have refined our understanding of this module and have brought us closer to being able to implement it in practical devices.

Some Abstracts concerning this work are enclosed below.

A NEURAL THEORY OF CIRCADIAN RHYTHMS: THE GATED PACEMAKER

Gail A. Carpenter and Stephen Grossberg

This article describes a behaviorally, physiologically, and anatomically predictive model of how circadian rhythms are generated by each suprachiasmatic nucleus (SCN) of the mammalian hypothalamus. This gated pacemaker model is defined in terms of competing on-cell off-cell populations whose positive feedback signals are gated by slowly accumulating chemical transmitter substances. These components have also been used to model other hypothalamic circuits, notably the eating circuit. A parametric analysis of the types of oscillations supported by the model is presented. The complementary reactions to light of diurnal and nocturnal mammals as well as their similar phase response curves are obtained. The "dead zone" of the phase response curve during the subjective day of a nocturnal rodent is also explained. Oscillations are suppressed by high intensities of steady light. Operations that alter the parameters of the model transmitters can phase shift or otherwise change its circadian oscillation. Effects of ablation and hormones on model oscillations are summarized. Observed oscillations include regular periodic solutions, periodic plateau solutions, rippled plateau solutions, period doubling solutions, slow modulation of oscillations over a period of months, and repeating sequences of oscillation clusters. The model period increases inversely with the transmitter accumulation rate but is insensitive to other parameter choices except near the breakdown of oscillations. The model's clocklike nature is thus a mathematical property rather than a formal postulate. A singular perturbation approach to the model's analysis is described.

A NEURAL THEORY OF CIRCADIAN RHYTHMS: ASCHOFF'S RULE IN DIURNAL AND NOCTURNAL MAMMALS

Gail A. Carpenter and Stephen Grossberg

A neural model of the circadian pacemaker within the suprachiasmatic nuclei (SCN) explains how behavioral activity, rest, and circadian period depend on light intensity in diurnal and nocturnal mammals. These properties are traced to the action of light input (external Zeitgeber) and an activity-mediated fatigue signal (internal Zeitgeber) upon the circadian pacemaker. Light enhances activity of the diurnal model and suppresses activity of the nocturnal model. Fatigue suppresses activity in both diurnal and nocturnal models. The asymmetric action of light and fatigue in diurnal vs. nocturnal models explains the more consistent adherence of nocturnal mammals to Aschoff's rule; the consistent adherence of both diurnal and nocturnal mammals to the circadian rule; and the tendency of nocturnal mammals to lose circadian rhythmicity at lower light levels than diurnal mammals. The fatigue signal is related to the sleep Process S of Borbély, and contributes to the stability of circadian period. Predictions include: diurnal mammals obey Aschoff's rule less consistently during a self-selected light-dark cycle than in constant light; if light level is increased enough during sleep in diurnal mammals to compensate for eye closure, then Aschoff's rule will tend to hold more consistently; nocturnal mammals which obey Aschoff's rule will either be arhythmic or violate Aschoff's rule if their fatigue signal is blocked before it can modulate their SCN pacemaker; in nocturnal mammals, there are SCN pacemaker cells where the effects of a light pulse and the fatigue signal summate; in diurnal mammals, a light pulse and the fatigue signal are mutually inhibitory at all SCN pacemaker cells; in both diurnal and nocturnal mammals, a light pulse excites some SCN cells and inhibits other SCN cells. The results are compared with those of Enright's model.

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* Supported in part by the Office of Naval Research

\+ Supported in part by the National Science Foundation

PROFESSIONAL PERSONNEL

1. Gail A. Carpenter (1/3 time)

   Senior Research Associate and Associate Professor of Mathematics, Northeastern University

   Ph.D., mathematics, University of Wisconsin, 1974

2. Stephen Grossberg (1/2 time)

   Professor and Director, Center for Adaptive Systems

   Ph.D., mathematics, Rockefeller University, 1967

3. Ennio Mingolla (full-time)

   Research Associate

   Ph.D., psychology, University of Connecticut, 1983

4. Cynthia Suchta (1/2 time)

   Program Coordinator

   B.A., English, Indiana University, 1982

<u>INTERACTIONS (COUPLING ACTIVITIES)</u>

January, 1983 - June, 1984

1. Two lectures, UCSD psychology department, 1/83
2. Boston University psychology department seminar, 2/83
3. Tufts University psychology colloquium, 3/83
4. University of Massachusetts (Boston) English department seminar, 3/83
5. Invited lecture to the annual Society of Biological Psychiatry meeting, New York, 4/83
6. University of Denver psychology colloquium, 4/83
7. Principal lecturers (14 hours) at interdisciplinary meeting on neural modelling, Scottsdale, Arizona, 4/83
8. Two invited lectures at the international meeting on synergetics of the brain, Bavaria, 5/83
9. Center work written up in 200 Newhouse News newspapers; in special issue of OMNI magazine on artificial intelligence and robotics; in U.S. News and World Report, etc.
10. Invited lecture at the international meeting of the European Society of Mathematical Psychology, Brussels, 9/83
11. Physics department seminar, Free University of Brussels, 9/83
12. Two presentations at the annual Society for Neuroscience meeting, 11/83
13. Northeastern University psychology colloquium, 12/83
14. Dartmouth College psychology colloquium, 1/84
15. Lecture at Sperling-Shiffrin interdisciplinary meeting, Teton Village, Wyoming, 1/84
16. University of Denver psychology colloquium, 1/84
17. First interdisciplinary Neuroscience Program colloquium, Boston University, 1/84
18. Lecture to AFOSR program managers, Bolling AFB, 2/84
19. Three lectures to Duke University psychology department, 3/84
20. Brown University mathematics colloquium, 4/84

21. Boston Philosophy of Science colloquium, 4/84

22. Two lectures to Einstein Medical School neurology department, 4/84

23. Three presentations to the annual ARVO meeting, Sarasota, 5/84

24. Two invited lectures at the international meeting on mathematical biology and differential equations, Dundee, Scotland, 6/84

25. Two invited lectures at the meeting on biomedical modelling and computer simulation, NIH, 6/84

Center members also carry out an extensive international correspondence with scientists in several disciplines, have begun inviting speakers to give interdisciplinary seminars, and train students in psychology, computer science, and engineering.